REMARKS

This Preliminary Amendment cancels the original claims, without prejudice, in the underlying PCT Application No. PCT/DE03/02145. The Preliminary Amendment also adds new claims 8-14. The new claims conform the claims to U.S. Patent and Trademark Office rules and do not add new matter to the application.

In accordance with 37 C.F.R. § 1.125(b), the Substitute Specification (including the Abstract) contains no new matter. The amendments reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to United States Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. §§ 1.121(b)(3)(ii) and 1.125(c), a Marked-Up Version of the Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. Approval and entry of the Substitute Specification (including Abstract) are respectfully requested.

The underlying PCT Application No. PCT/DE03/02145 includes an International Search Report, dated October 29, 2003, a copy of which is submitted herewith.

Applicants assert that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully submitted,

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GMR SENSOR ELEMENT AND ITS USE

Field Of The Invention

The present invention relates to a GMR sensor element according to the main claim, as well as its use.

Background Information

The giant magneto-resistive effect (GMR effect) may be utilized, in the form of so-called spin-valve structures ("spin-valves") for angular-position sensing. This is described, for example, in *PCT International Publication No.* WO 00/79298 or in ~~EP~~*European Published Patent Application No.* 0 905 523 A2.

GMR spin-valves are made up in essence of two ferromagnetic thin films having a resulting magnetization m_1 or m_2, which are separated from each other by a nonmagnetic thin film lying in between. The electrical resistance $R(\alpha)$ of such a layer system then shows a cosine-type function of the angle α between the direction of magnetization m_1 and the direction of magnetization m_2 of the form:

$$R(\alpha) = \overline{R} - 0.5 \cdot \Delta R_{GMR} \cdot \cos(\alpha)$$

In this context, the maximum relative resistance change

$\Delta R_{GMR} / \overline{R}$ designates the GMR effect, and typically amounts to 5% to 10%. GMR spin-valve layer systems, by the way, are usually deposited with the aid of cathode sputtering of the respective materials, and then structured using customary photolithography methods and etching techniques.

What is essential for the intended spin-valve function is a rigid, at least approximately not changeable direction of magnetization m_1 of the first ferromagnetic layer, of the so-called reference layer (RL), because of a magnetic field, acting from outside on the layer system, that is to be detected particularly with regard to its direction and/or strength, and a direction of magnetization, m_2, of the second ferromagnetic layer, of the so-called free layer (FL) or

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detection layer, that orients itself slightly, at least approximately parallel to the outer magnetic field. In order to achieve both of these, on the one hand, the two ferromagnetic layers are magnetically decoupled by a sufficient thickness of the nonmagnetic intermediate layer, of the so-called nonmagnetic layer (NML), of typically a few nanometers, and the magnetization of the reference layer (RL) is fixed or "pinned", for instance, by an additional, directly adjacent antiferromagnetic layer, a so-called natural antiferromagnet (AF), and by its mutual magnetic coupling by exchange interaction.

This is shown schematically in Figure 1a, where the GMR layer system or GMR sensor element is under the influence of a magnetic field of a magnetic transducer.
One may achieve a further improved stabilization of the reference magnetization by adding an additional so-called synthetic or "artificial" antiferromagnet (SAF). This SAF, corresponding to Figure 1b, is made up of two ferromagnetic layers that is strongly antiferromagnetically coupled via a nonmagnetic intermediate layer. The ferromagnetic layer of these two, which lies directly next to or on the natural antiferromagnet AF, is designated as the pinned layer (PL), since its magnetization MR is fixed or "pinned" as a result of the coupling with the natural antiferromagnet (AF). The second ferromagnetic layer of the SAF, whose magnetization MR is oriented opposite to that of the pinned layer (PL) as a result of the antiferromagnetic coupling, is used as reference layer (RL) for the abovementioned GMR spin-valve layer system.

In order to extract the angle-dependent useful signal, in a GMR sensor element according to the related art, four spin-valve resistance elements are connected together to form a Wheatstone's bridge circuit (Wheatstone's full bridge), such as by using an aluminum thin film track conductor. The maximum signal amplitude is obtained by, as in Figure 2, oppositely oriented reference magnetizations MR of the bridge resistors within the half bridges and similarly oriented reference magnetizations MR of the resistors lying diagonally in the full bridge.

As a rule, a GMR angle sensor also has a second full bridge of GMR resistors, whose reference directions, as shown in Figure 2, are rotated by 90^0 to the ones of the first bridge. Signal U_{sin} made available by the second full bridge is thereby phase-shifted by 90^0 with respect to the signal of the first full bridge U_{cos}.

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By arctangent formation or corresponding algorithms (such as the CORDIC algorithm) one then determines, from the two cosine-shaped or sine-shaped bridge signals U_{sin}, U_{cos}, the angle α, that is single-valued over a full 360^0 revolution, to the direction of an outer magnetic field B.

The different reference magnetization directions according to Figure 2 are, for instance, implemented in that the individual GMR bridge resistors are heated locally to a temperature T above the blocking temperature (Néel temperature) of the antiferromagnetic layer (AF), but below the Curie temperature of ferromagnetic layers (PL, RL) as in Figure 1a or 1b, so that the antiferromagnetic spin order in the antiferromagnetic layer is canceled, and thereafter they are cooled in an outer magnetic field of a suitable field direction. In the renewed formation, taking place in this context, of the antiferromagnetic order, the spin configuration resulting from the exchange interaction at the interface of antiferromagnetic layer (AF) and adjacent ferromagnetic layer (PL) is frozen. As a result, the direction of magnetization of the adjacent ferromagnetic layer (pinned layer PL) is fixed. The local heating of the GMR bridge resistors may take place, for example, with the aid of a brief laser pulse or current pulse. The current pulse may be driven, in this context, directly by the GMR conductor structure or/and an additional heating conductor.

In the case of known GMR angle sensors, reference magnetization MR of the individual bridge resistors is selected to be either parallel or perpendicular to the direction of the strip-shaped structured GMR resistor elements. This is used to hold the influence of the shape anisotropy to a low value. Furthermore, the strip-shaped structured GMR resistor elements are preferably aligned in parallel within a full bridge according to Figure 2. This is used to suppress a signal contribution because of a superimposed anisotropic magnetoresistive effect (AMR effect). The AMR signal contribution is based, in this context, on a function of the electric resistance of the angle α between the current direction and the magnetization direction of the form:

$$R(\vartheta) = \overline{R} + 0.5 \cdot \Delta R_{AMR} \cdot \cos(2 \cdot \vartheta)$$

If, on the other hand, the GMR resistors are implemented within a half bridge and having orthogonal alignment of their GMR strips, as is the case, for example, in Figure 10 in *PCT International Publication No.* WO 00/79298, then the AMR signal contribution is even

maximally favored. That acts in a worsening manner on the angular accuracy of the GMR angle sensor.

Summary ~~of the~~ *Of The* Invention

For the reasons mentioned, therefore, known GMR angle sensors have no rotationally symmetrical positioning of the bridge resistors. Rather, both full bridges are usually positioned laterally next to each other. Therefore, as a result of the lacking rotational symmetry, a heightened sensitivity of known sensors comes about with respect to the directional inhomogeneity of the transducer field, i.e. of the magnetic field acting from the outside, as well as with respect to temperature gradients.

Because, in known GMR angle sensors, the pinning direction or reference direction within a bridge resistor always has a fixed angle to the strip direction, these sensors do not further offer the possibility of compensating for shape anisotropy-conditioned influences on the pinning behavior and such disadvantages on the accuracy of the angular sensing.

By contrast, for an angular sensor that records over 360^0, rotational symmetry in the sensor design is a great advantage, so that one does not obtain additional, direction-dependent angular error contributions, just because of an asymmetry in the positioning of the individual GMR resistor elements.

Therefore, because of the rotationally symmetrical positioning of the GMR resistor elements in the two Wheatstone's bridges, both a reduced sensitivity with respect to field direction inhomogeneities and temperature inhomogeneities is achieved and an undesired AMR signal contribution is suppressed, and, furthermore, the shape anisotropy influence on the pinning behavior and the angle sensing accuracy of the GMR sensor element is reduced.

It is also especially advantageous if, besides the rotationally symmetrical positioning of the GMR resistor elements in the two Wheatstone's bridges, an interleaved positioning of the resistors with each other is selected. This leads to a further reduced sensitivity to field direction inhomogeneities and temperature inhomogeneities.

The suppression of the interfering AMR signal contribution is achieved by an additional subdivision of every single GMR bridge resistor element into two equal halves, or partial bridge resistors, having GMR strip directions that are oriented orthogonally to one another. This particularly also leads to an increase in angular measurement accuracy. It is also

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advantageous, in this connection, that, because the direction of the strip-shaped structured GMR resistor elements ("GMR strip direction") is selected for respectively one of the two partial bridge resistors to be parallel, and is selected for respectively the other of the partial bridge resistors to be perpendicular to the pinning direction or reference direction, an averaging comes about of the influence of pinning directions parallel and perpendicular to the strip direction within each of the GMR bridge resistor elements. The pinning behavior is then, in turn, identical for all two-part GMR bridge resistor elements (average of two parts, in each case). In this case, the two bridge output signals U_1, U_2 advantageously also have a 45^0 phase shift with respect to each other.

If the GMR resistor elements have a pinning direction or a reference direction which has been selected to be at least approximately less than 45^0 to the direction of the strip-shaped structured GMR resistor elements, this leads advantageously to an identical pinning behavior of the individual GMR resistor elements, i.e. especially to an improved signal stability and long-term stability of the GMR sensor element. In this case, the two bridge output signals U_1, U_2 also have a 45^0 phase shift with respect to each other.

Bridge output signals U_1, U_2, that are phase-shifted by any desired angle v to each other, v being preferably 45^0 or around 45^0, may finally, advantageously, be imaged by a coordinate transformation to orthogonal signals having a 90^0 phase shift. From the latter, the angle α, being sought after, to the direction of outer magnetic field B may be determined, by arctangent formation or a corresponding algorithm, such as the CORDIC algorithm. Beyond this, the coordinate transformation offers the advantage that production-caused fluctuations in the phase difference of the two bridge signals U_1, U_2 are able to be adjusted during the imaging on the orthogonal signals.

Brief Description ~~of the~~*Of The* Drawings

Figure 1a   shows a simplified GMR spin-valve layer construction having two ferromagnetic layers RL and FL that have magnetizations m_1 and m_2, one nonmagnetic intermediate layer NML and an antiferromagnetic layer AF. The latter is used for fixing (pinning) reference magnetization m_1. In addition, a magnetic transducer is provided for generating an outer magnetic field B. The angle α designates the angle between the field direction or magnetization direction of the free ferromagnetic layer (FL), and thus also the direction of the outer magnetic field B in the plane of the GMR sensor element, and the reference magnetization direction.

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Figure 1b   shows a GMR spin-valve layer system having a natural antiferromagnet AF and an additional synthetic antiferromagnet SAF, as well as an additional nonmagnetic intermediate layer NML and a ferromagnetic free layer FL.

Figure 2   shows an equivalent circuit diagram for an angle sensor element based on the GMR effect having two full bridges (Wheatstone's bridge circuits), the reference magnetization MR being oriented pairwise opposite within the two bridges, and being rotated from bridge to bridge by 90^0 with respect to each other. The direction of reference magnetization MR further is parallel or perpendicular to the direction of the individual, strip-shaped structured GMR resistor elements, which are constructed, for example, as in Figure 1a or 1b. This "strip direction" is represented by the indicated strip set within the individual GMR resistor elements. Besides that, in Figure 2 the direction of an outer magnetic field B is indicated, which, together with a reference direction, subtends the angle α that is is to be measured using the GMR sensor element. The reference direction or zero direction is, in this context, specified by the selection of the reference magnetization directions in the two full bridges, of which one is designed as a sine full bridge and one as a cosine full bridge.

Figure 3   shows a rotationally symmetrical device of meandering, interleaved GMR bridge resistor elements 1/1 to 1/4 (bridge 1) and 11/1 to 11/4 (bridge 11). In this context, the directions of the reference magnetization (see arrows marked in Figure 3) in bridge 1 are in each case oriented at less than 45^0 to the direction of the individual strip-shaped structured GMR resistor elements, and the reference magnetization directions in bridge 11 are rotated in each case by 45^0 with respect to those in bridge 1. Besides that, in Figure 3 the direction of an outer magnetic field B is indicated, which, together with a reference direction, subtends the angle α that is to be measured using the GMR sensor element. The reference direction or zero direction is, in this context, specified by the selection of the reference magnetization directions in bridge 1 and bridge 11, bridge 1 being supposed to supply a cosine-shaped signal curve over the angle α.

Figure 4   shows an equivalent circuit diagram to the layout of the GMR sensor element according to Figure 3. The pinning or reference magnetization direction MR is, in this context, in each case oriented at less than 45^0 to the GMR strip direction, which is, analogously to Figure 2, once more indicated by the strip set drawn in inside the individual GMR resistor elements, and in bridge 11 is rotated additionally by 45^0 with respect to that in

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bridge 1. A strengthening of the AMR signal contribution comes about as a result of strip directions of the resistors of each half bridge that are orthogonal to one another.

Figure 5a   shows GMR sensor output signals U_1 and U_2 having a 45^0 phase difference according to a pinning direction or reference magnetization direction MR less than 45^0 to the strip direction, corresponding to Figure 3 and 4.

Figure 5b   shows correspondingly transformed GMR sensor signals U_{cos} and U_{sin} that are orthogonal to each other, having a 90^0 phase difference. The AMR signal contribution is not shown in Figure 5a and Figure 5b. The direction of outer magnetic field B in degrees, i.e. the angle α, is in each case plotted on the x axis in Figure 5a and 5b, while on the y axis there is plotted, in Figure 5a the GMR sensor output signal in mVolt/Volt, and in Figure 5b the transformed GMR sensor signal in mVolt/Volt.

Figure 6   shows a rotationally symmetrical, at least approximately circular or octagonal, interleaved positioning of meandering GMR bridge resistor elements, a suppression of the AMR signal contribution having been undertaken by subdividing each of the individual bridge resistor elements into two equal halves having strip directions that are orthogonal to one another.

Figure 7   shows an equivalent circuit diagram to the GMR resistor elements as in Figure 6. Suppression of the AMR signal contribution is here achieved by subdividing each bridge resistor element I/1,I/2 to II/4 into two halves a and b, having GMR strip directions that are orthogonal to one another. The respective pinning magnetization or reference magnetization MR is less than 45^0 to the respective GMR strip direction. The latter is indicated by the strip set drawn in within the individual GMR resistor elements.

Figure 8   shows an equivalent circuit diagram to the layout of the GMR resistor elements according to Figure 6, having pinning magnetization directions or reference magnetization directions MR, alternative to Figure 7, of less than 0^0 and 90^0 to the GMR strip direction at each of the individual bridge resistors I/1, I/2 to I/4. The averaging of the influence of the pinning direction takes place here by pinning direction or reference magnetization direction, both parallel and perpendicular to the GMR strip direction, within each two-part bridge resistor I/1, I/2 to I/4.

a.) rotationally symmetrical positioning

Figure 3 shows a possible rotationally symmetrical positioning of altogether eight bridge resistor elements of two full bridges (Wheatstone's bridges). In contrast to AMR sensors, in which the reference direction is given by the current direction which is specified by the strip direction, in the case of the GMR angle sensor, the reference direction is specified by the direction of the magnetization of reference layer (RL). In principle, the pinning direction or reference direction may, in this context, be selected as desired, however, in order to obtain the same pinning behavior for all bridge resistor elements, in this case an orientation of the pinning direction or reference direction is selected that is less than 45^0 to the strip direction. This is made even clearer in Figure 4, where, besides the strip direction (strip set inside the resistor symbols) the direction of the reference magnetization MR is also given.

b.) imaging on orthogonal signals

In the case of a pinning direction or a direction of the reference magnetization less than 45^0 to the GMR strip direction, according to Figure 5a the two bridge output signals U_1 and U_2 do not have the usual phase shift of 90^0, but only a phase shift of 45^0. These signals U_1 and U_2 may, however, be transformed in a simple manner to the orthogonal, cosine-shaped and sine-shaped signals according to Figure 5b. To do this, the following transformation is performed in a sensor evaluation electronic device:

$$\begin{pmatrix} U_{cos} \\ U_{sin} \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ \dfrac{\cos(\varphi)}{\sin(\varphi)} & \dfrac{-1}{\sin(\varphi)} \end{bmatrix} \bullet \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} = \begin{pmatrix} U_1 \\ \dfrac{U_1 \cdot \cos(\varphi) - U_2}{\sin(\varphi)} \end{pmatrix}$$

In this equation, ν denotes the phase shift of the second bridge signal with respect to the first bridge signal. This phase shift may, in principle, be selected as desired, but preferably a phase shift of 45^0 is set.

From the cosine-shaped and sine-shaped signals obtained with the aid of this transformation, according to Figure 5b, one may determine the angle α by arctangent formation or by applying a corresponding algorithm, such as the CORDIC algorithm in the sensor electronic system:

$$\alpha_{mess} = \arctan\left(\frac{U_{\sin}}{U_{\cos}}\right)$$

The implementation of this coordinate transformation further offers the important advantage that production-conditioned fluctuations in the phase shift of the two bridge signals U_1, U_2 are able to be detected specifically as to the sensor during imaging to the orthogonal signal (90⁰ phase shift) and compensated for. To do this, for example in an offset adjustment or amplitude adjustment of the signals U_1, U_2 at the end of a production line, this phase shift v is also determined, for example, using Fourier analysis of the two bridge signals U_1, U_2, and is stored in the sensor evaluation electronic system.

c.) rotationally symmetrical positioning having suppression of the AMR signal contribution

The resistor positioning shown in Figure 3 favors the AMR signal contribution, since the GMR strip directions of the two bridge resistors of each half bridge are orthogonal to each other. This disadvantage may be avoided in that, according to the preferred, also rotationally symmetrical positioning according to Figure 6, one puts together each bridge resistor from two equal halves having GMR strip directions that are perpendicular to each other. Because of the series connection of the two partial resistors each having identical reference magnetization MR, the AMR component is then filtered out, while the GMR signal component remains unchanged as a result of the identical direction of reference magnetization MR in the case of both partial resistors. This situation is made clearer by the following relationship for a two-part GMR bridge resistor element:

$$R(\alpha) = \underbrace{\frac{1}{2} \cdot \left(\overline{R} - 0.5 \cdot \Delta R_{GMR} \cdot \cos(\alpha) + 0.5 \cdot \Delta R_{AMR} \cdot \cos(2\vartheta)\right)}_{1.\textit{Teilwiders} \tan d}$$

$$+ \underbrace{\frac{1}{2} \cdot \left(\overline{R} - 0.5 \cdot \Delta R_{GMR} \cdot \cos(\alpha) + 0.5 \cdot \Delta R_{AMR} \cdot \cos\left(2(\vartheta - 90^\circ)\right)\right)}_{2.\textit{Teilwiders} \tan d}$$

$$= \overline{R} - 0.5 \cdot \Delta R_{GMR} \cdot \cos(\alpha)$$

In this equation, α denotes the angle between field direction and magnetization direction of the free ferromagnetic layer (FL) and the reference magnetization direction; ϑ denotes the

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angle between the field direction or magnetization direction of the free layer (FL) and the GMR strip direction of the first partial resistor. The strip direction of the second partial resistor is rotated by -90^0 with respect to the first partial resistor.

d.) pinning behavior

Figure 7 makes clear the subdivision of the bridge resistors into two halves in each case, having strip directions that are orthogonal to each other, but having an identical reference magnetization direction MR. In principle, the pinning direction and the direction of reference magnetization MR may be selected as desired. However, an angle of 45^0 to the respective strip direction is preferred, because thereby an identical pinning behavior is achieved for all partial resistors.

Alternatively, one may also set a pinning direction or a direction of reference magnetization MR which is oriented respectively parallel to the strip direction for one of the two partial resistors and respectively perpendicular to the strip direction for the other of the two partial resistors. It is true that thereby one achieves a different pinning behavior in the case of the individual partial resistors, however, overall again an identical pinning behavior is achieved in the case of each of the bridge resistor elements in the form of a series connection of the two partial resistors.

Compared to known sensors, this selection of the pinning direction or reference magnetization direction yields the advantage that, inside each bridge resistor element, via the different pinning behavior of parallel and perpendicular alignment of the pinning direction or the reference magnetization direction to the GMR strip direction, an average value comes about.

The 360^0 GMR angle sensor described is especially suitable for the detection of the absolute position of the camshaft or the crankshaft in a motor vehicle, particularly in the case of a camshaft-free engine having electrical or electrohydraulic valve timing, of a motor position of an electrically commutated motor, or of detection of a windshield wiper position, or in the steering angle sensor system in motor vehicles.

Abstract *Of The Disclosure*

A GMR sensor element is proposed, having a rotationally symmetrical positioning of especially eight GMR resistor elements which are connected to each other to form two Wheatstone's full bridges. This GMR sensor element is especially suitable for use in an angle sensor for the detection of the absolute position of the camshaft or the crankshaft in a motor vehicle, particularly in the case of a camshaft-free engine having electrical or electrohydraulic valve timing, of a motor position of an electrically commutated motor, or of detection of a windshield wiper position, or in the steering angle sensor system in motor vehicles.

~~Figure 3~~